

Environmental Control and Life-support Subsystem (ECLSS)

4.4.1

In This Chapter You'll Learn to...

- Describe the main functions and requirements of the communication and data-handling subsystem (CDHS)
- Describe the main functions and requirements of the electrical power subsystem (EPS)
- Describe the main functions and requirements of the environmental control and life-support subsystem (ECLSS)
- Describe the main functions and requirements of a spacecraft's structures and mechanisms

Outline

4.4.1.1 Environmental Control and Life-support Subsystem (ECLSS)

4.4.1.2 System Overview

4.4.1.3 Basic Principles of Thermal Control

Heat Sources in Space
Heat Transfer
Methods for Spacecraft Thermal Control

4.4.1.4 Basic Principles of Life Support

Oxygen
Water and Food
Waste Management
Closed-loop Life Support

4.4.1.5 Systems Engineering

Requirements and Constraints
Analysis and Design
Testing

4.4.1.1 Environmental Control and Life-support Subsystem (ECLSS)

In This Section You'll Learn to...

- Explain the main function of the environmental control and life-support subsystem—thermal control and life support

As we know from Section 4.1.2, space is a rough place to live and work—for humans and machines. For spacecraft to survive, and even thrive, we need some way to keep the payload and all the subsystems onboard (including the crew) healthy and happy, as shown in Figure 4.4.1-1. Providing a livable environment in the harshness of space is the function of the environmental control and life-support subsystem (ECLSS).

We can divide the tasks of the ECLSS conceptually into two problems—thermal control and life support. In this section, we'll focus primarily on the thermal-control problem—the major concern for uncrewed spacecraft. Then we'll introduce some of the other complications caused by placing fragile humans onboard. Finally, we'll look at some of the major systems-engineering issues of ECLSS design.



Figure 4.4.1-1. Healthy and Happy “Payloads.” The job of the environmental control and life-support subsystem (ECLSS) is to provide a comfortable environment for subsystems and payloads, including astronauts, to live and work. (Courtesy of NASA/Johnson Space Center)

Section Review

Key Concepts

- A spacecraft’s environmental control and life-support subsystem (ECLSS) has two main tasks—environmental control (primarily temperature) and life support

4.1.1.2 System Overview

In This Section You'll Learn to...

??

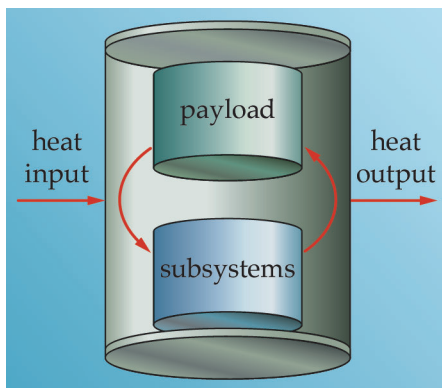


Figure 4.4.1-2. Thermal Control. The challenge of spacecraft thermal control is to balance the heat input plus the heat produced internally with the heat output to maintain thermal equilibrium.

A spacecraft orbiting peacefully in space is perhaps the ultimate example of an isolated system. We can quite easily analyze everything that goes in and out. One of those things is heat. If more heat goes into a spacecraft, or is produced internally, than leaves it, then its temperature increases. If more heat leaves than goes in, it begins to cool. Because sensitive equipment and payloads (including humans) can't survive wide temperature swings, we need to balance the heat flow in, plus the heat generated internally, with the heat flow out. We'd prefer the spacecraft's average temperature to stay nearly constant, a condition we call *thermal equilibrium*.

The main job of the thermal-control part of the ECLSS is to regulate and control the amount of heat that gets in, goes out, and moves around inside a spacecraft. Just as the furnace and air conditioner do in our homes, the thermal-control subsystem regulates and moderates the spacecraft's temperature. To maintain thermal equilibrium, the ECLSS must balance inputs and outputs, as well as internal heat sources. This means the heat coming in plus the heat produced internally must equal the total heat ejected.

$$\text{Heat Out} = \text{Heat In} + \text{Internal Heat (for thermal equilibrium)}$$

Figure 4.4.1-2 shows a simple view of the thermal control inputs and outputs, and illustrates the flow of heat between payloads and subsystems.

Section Review

Key Concepts

- ??
-

4.1.1.3 Basic Principles of Thermal Control

In This Section You'll Learn to...

- List the main sources of heat for a spacecraft
- Describe the three basic means of heat transfer—conduction, convection, and radiation—and how to use them on a spacecraft
- Describe the various ways to control heat outside and inside a spacecraft

Later we'll see what techniques the thermal control subsystem uses to control this heat flow. But first, we'll review some internal and external heat sources for spacecraft. Following this, further discussion of thermal control methods requires an understanding of basic thermodynamics, so we'll review some of the principles of heat transfer.

Heat Sources in Space

Typically, the biggest problem for spacecraft thermal control is removing heat. For the most part, we must maintain temperatures inside even unmanned spacecraft at normal room temperature (20°C or about 70°F). In some cases, specific payloads may have more demanding requirements. Infrared sensors, for example, require refrigeration units to supercool them to 70 K (-193°C or -316°F).

As Figure 4.4.1-3 shows, heat in space comes from three main sources

- The Sun
- Earth
- Internal sources

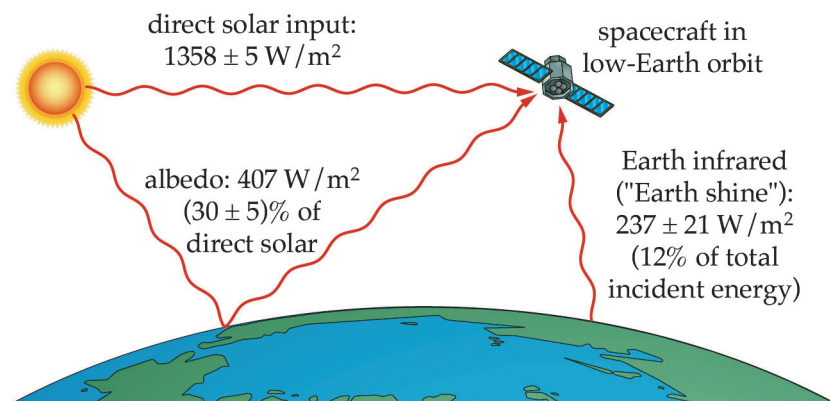


Figure 4.4.1-3. Heat Sources in Space. A spacecraft gets heat from the Sun, Earth (reflected and emitted energy), and from within itself.

Near Earth, the biggest source of heat for orbiting spacecraft is the Sun—about 1358 W/m^2 . We all know how hot we get standing in the Sun on a summer day. For a satellite in space, the Sun's heat is much more intense because no atmosphere absorbs radiant energy and moderates the temperature. On the side facing the Sun, the surface of a spacecraft can reach many hundreds of degrees Kelvin. On the side away from the Sun, the temperature can plunge to a few degrees Kelvin.

So what is the temperature in space? Earth is about 300 K, while temperatures in space range from 900–1300 K. Sounds hot, but is it? On Earth we measure temperature using a thermometer. The fluid in the thermometer expands when heated by air molecules brushing by it. Temperature is proportional to the velocity and number of the molecules. In space, the molecules are traveling faster but there aren't very many of them. So although the temperature appears higher in space, the effect on people and materials is much less than the equivalent temperature on Earth.

For satellites in low-Earth orbit, Earth is also an important source of heat because of two effects. The first results from sunlight reflecting off Earth—called *albedo*. It accounts for as much as 407 W/m^2 , or 30% of the direct solar energy on a spacecraft. Another important source is “Earth shine,” or the infrared energy Earth emits directly, as a result of its temperature. This accounts for another 237 W/m^2 or about 12% of the incident energy that hits a spacecraft.

Internal sources also add heat. Electrical components running onboard and power sources such as radioisotope thermoelectric generators (RTGs) produce waste heat. If you've ever placed your hand on the top of your television after it's been on a while, you know how hot it can get. In your living room, the heat from the television quickly distributes throughout the room because of small air currents. Otherwise, your television would overheat and be damaged. Unfortunately, it's not so easy to keep spacecraft temperatures balanced onboard. We'll see what methods are available for moving heat around, next.

Heat Transfer

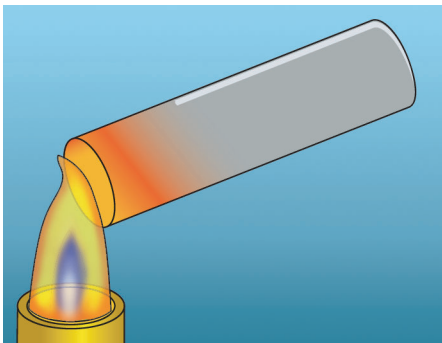


Figure 4.4.1-4. Conduction. Conduction occurs when heat flows through a physical medium from a hot point to a cooler point.

Recall from Chapter 3 that heat transfers from one point to another through

- Conduction
- Convection
- Radiation

Let's start with conduction. If you hold one end of a long metal rod and put the other end into a fire, as in Figure 4.4.1-4, what happens? You get burned! The heat from the fire somehow flows right along the metal rod. When heat flows from hot to cold through a physical medium (in this case the rod), we call it *conduction*, and we experience it every day. It's the reason we put insulation in the walls of our home to prevent heat from the inside being conducted outside (and vice versa in the summer time).

Heat will flow faster if the material is a better heat *conductor*, such as metal rather than wood. It also will flow faster if a larger area is available, if the temperature difference is greater, or if the distance is smaller. We use this principle to insulate the walls in our homes by building thick walls and filling them with poor heat conductors (insulators).

The second method of heat transfer is convection. If you've ever boiled water, you've used convection. Let's look at how water boils in a pot on the stove, as illustrated in Figure 4.4.1-5. Water on the bottom of the pot, nearest the heat source, gets hot first, through conduction, directly from the heat source. As the water gets hot, it expands slightly, making it a bit less dense than the water above it. At the same time, gravity pulls heavier material to the bottom of the pot. Thus, the cooler, denser water at the top of the pot displaces the warmer, less dense water at the bottom.

Once on the bottom, this cooler water also heats, expands, and rises. A convection current then continues as water flows past the heat source, driven by the force of gravity, until it reaches thermal equilibrium (heat boils out the top at the same rate the stove adds heat on the bottom). Unlike conduction, which relies on heat flow *through* a solid medium, *convection* transfers heat to a fluid medium flowing past a heat source. Obviously, if the fluid is flowing, something must make it flow. Convection relies on gravity, or some other force, to push the fluid past the heat source.

In the free-fall environment of space, no forces cause cooler water to replace the warmer water (everything free falls together). For convection to work in space, we must supply the force to move the fluid. For example, Russian spacecraft have long relied on forced convection to cool their spacecraft electronics. The components are in a large pressure vessel filled with nitrogen at about 1 bar pressure (14.7 p.s.i.). They use fans to circulate the nitrogen around the vessel, cooling the electronics. Figure 4.4.1-6 shows one of the Russian *Meteor* spacecraft that relies on this method of thermal control.

The final method of heat transfer is radiation. If you've ever basked in the warm glow of an electric space heater, you've felt the power of heat transfer by radiation. *Radiation* is the means of transferring energy (such as heat) through space. More specifically, radiative heat transfer occurs through electromagnetic (EM) radiation. As we described in Chapter 11, EM radiation is the waves (or particles) emitted from an energy source. Recall that a red-hot piece of metal acts as a blackbody radiator, meaning the intense heat energy causes it to emit EM radiation. In this case, the frequency of the EM radiation is in the visible (red) portion of the EM spectrum. We use Stefan-Boltzmann's Law to describe the heat-power transfer by radiation.

Important Concept

Stefan-Boltzmann relationship: The energy emitted by an object depends on its temperature and its basic ability to store or give off heat (its emissivity).

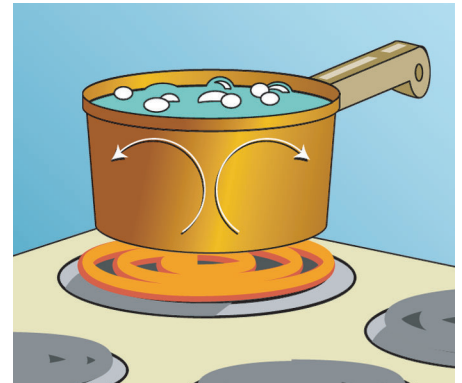


Figure 4.4.1-5. Convection. Convection occurs when some driving force, such as gravity, moves the medium (usually a liquid or gas) past a heat source.

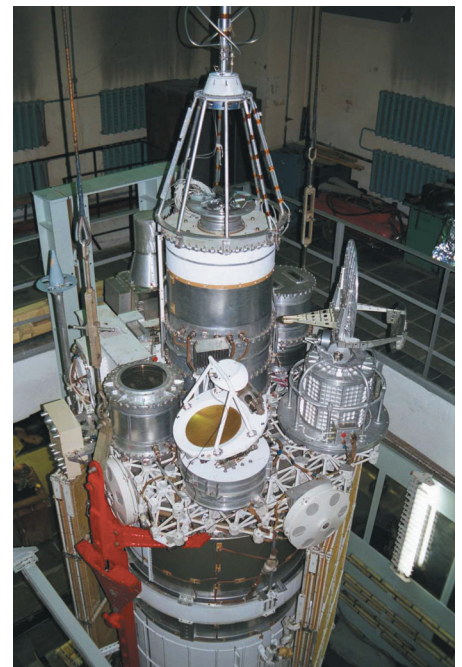
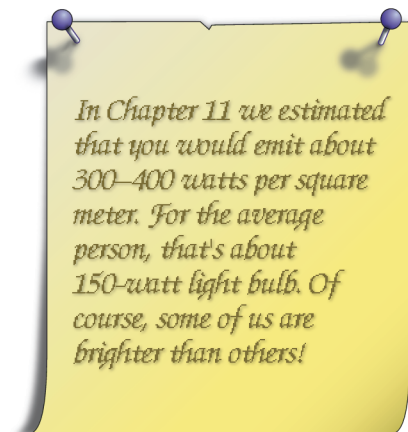


Figure 4.4.1-6. Meteor Spacecraft. The Russian Meteor spacecraft is able to use convective cooling of onboard electronics by sealing everything in a large pressure vessel and using fans to circulate nitrogen. (Courtesy of A. Koobanoff and C. Maag)



Equation (4.4.1-1) summarizes this relationship.

$$E = \epsilon \sigma T^4 \quad (4.4.1-1)$$

where

E = object's energy per square meter (W/m^2)

ϵ = object's emissivity ($0 < \epsilon < 1$)

σ = Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W}/\text{m}^2 \text{ K}^4$)

T = object's temperature (K)

This relationship tells us that, as the temperature of a black body increases, the amount of heat power it emits increases by the fourth power of the temperature. Thus, if we double the temperature, the amount of energy emitted will increase sixteen times.

As Figure 4.4.1-7 shows, when radiation strikes a surface, the material reflects, absorbs, or transmits it. Reflected radiation is the same as reflected light from a mirror. This type of radiation basically bounces off the surface. We use the symbol, ρ , to identify the *reflectivity* of a surface. We work with reflectivity as a percentage; that is, $\rho = 0.3$ means that an object reflects 30% of the radiation that hits it.

Absorbed radiation is energy the surface captures, just as a sponge soaks up water. Absorbed radiation eventually causes the surface temperature to rise. We use the symbol, α , to identify absorptivity. We also work with *absorptivity* as a percentage; that is, $\alpha = 0.5$ means an object absorbs 50% of the radiation that hits it.

Transmitted radiation is energy that passes right through (the same as visible light passes through a pane of glass). We use the symbol τ to quantify transmissivity. *Transmissivity* too is a percentage; that is, $\tau = 0.2$ means an object transmits 20% of the radiation that hits it.

Because of the conservation of energy, all of the radiation must go somewhere. So the sum of the reflected, absorbed, and transmitted radiation energy equals the incoming energy.

Thus transmissivity is the percent of the incoming radiation that passes through the material; absorptivity is the percent of incoming radiation that is absorbed by the material; and, reflectivity is the percent of the incoming radiation that is reflected off the material.

τ = transmissivity ($0 < \tau < 1$)

α = absorptivity ($0 < \alpha < 1$)

ρ = reflectivity ($0 < \rho < 1$)

As an object absorbs energy, the kinetic energy of individual molecules increases and the object gets hotter. As Figure 4.4.1-8 shows, all objects above absolute zero (0 K) emit radiation. But not all materials emit heat with the same efficiency. We call a material's ability to emit heat its *emissivity*, ϵ . A pure black body has an emissivity of 1.0. The black tiles on the Space Shuttle have a very high emissivity ($\epsilon = 0.8$).

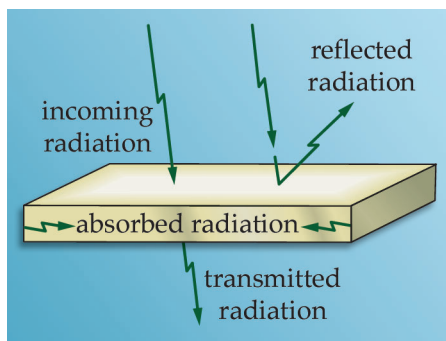


Figure 4.4.1-7. Radiation. Radiation striking a surface is either reflected, absorbed, or transmitted.

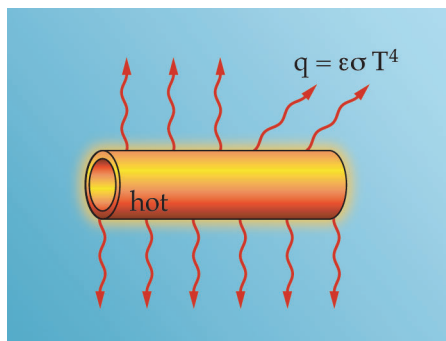


Figure 4.4.1-8. Emissivity. Any object with a temperature above 0 K (meaning basically everything in the universe) emits (EM) radiation per the Stephan-Boltzmann relationship. The greater the emissivity of a material the more energy it emits at a given temperature.

Methods for Spacecraft Thermal Control

Now that we've explored the heat transfer options, let's see how we use them to maintain spacecraft thermal equilibrium. As we said earlier, we must manage heat coming into and out of the spacecraft (external thermal control), as well as heat generated inside (internal thermal control).

There are two basic approaches to thermal control. The easiest method is passive thermal control. *Passive thermal control* is an open-loop means of controlling the spacecraft's temperature, by carefully designing the entire system to regulate heat input and output, and creating convenient heat conduction paths. The nice thing about passive thermal control is, once it gets going, it requires no additional control inputs. Unfortunately, some systems have too much heat to control or the environment is too unpredictable. In these situations, we resort to closed-looped, active thermal control. *Active thermal control* employs working fluids, heaters, pumps, and other devices to move and eject heat. Next, we'll look at methods for external thermal control.

External Thermal Control. The challenge of external thermal control is to manage the flow of heat into and out of a spacecraft. Let's start with the problem of heat input.

We know the main external heat sources are the Sun and Earth. Our first line of defense is to carefully control the amount of heat absorbed by spacecraft surfaces. Recognize that, in the vacuum of space, the side facing the Sun gets terribly hot and the side facing space gets terribly cold. One of the simplest ways to balance this temperature differential is to slowly rotate the spacecraft around an axis perpendicular to the Sun. In this "barbecue" mode, a spacecraft surface alternately heats when facing the Sun and then cools when facing the cold of space, maintaining a moderate surface temperature without hot spots. The Apollo spacecraft used this method all the way to the Moon and back. This is one method of active thermal control of heat input.

The barbecue mode can help to equalize the heat hitting the surface. The next challenge is to control the amount that gets absorbed. As we've seen, depending on the material, it absorbs, reflects, or transmits incident radiation. By changing the type of surface coatings on the spacecraft, we can control its total absorptivity and emissivity, thus its equilibrium temperature. We can change the ratio of heat absorbed to emitted (α/ϵ) by carefully selecting materials to keep the surface temperature at a desired level.

Instead of actually coating the metallic surface of the spacecraft structure, we place various types of multi-layer insulation (MLI) on top of the structure. MLI consists of alternating sheets of polymer material, such as Mylar™ or Kapton™. Kapton™ often looks like gold foil and is similar to the "space blankets" sold in sporting goods stores to keep you warm during emergencies (another great spin-off from space technology!). We can apply MLI or simply Mylar™ or Kapton™ adhesive tape to surfaces to vary the amount of heat absorbed by different areas and insulate the subsystems underneath. Typically, we can meet nearly 85% of a

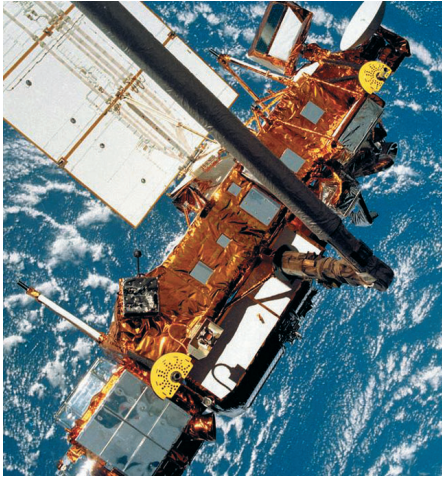


Figure 4.4.1-9. Upper Atmospheric Research Satellite (UARS). We can meet nearly 85%–100% of a spacecraft's thermal-control demands by choosing the right coatings and insulation. Here we see foil wrapping used on the UARS. (Courtesy of NASA/Goddard Space Flight Center)

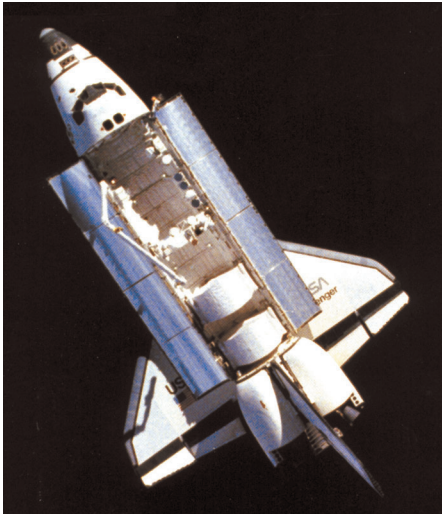


Figure 4.4.1-10. Space Shuttle Radiators. Radiators, like the ones on the inside of the Space Shuttle's payload bay doors, are areas of low absorptivity and high emissivity that radiate heat transferred to them. (Courtesy of NASA/Johnson Space Center)

spacecraft's thermal-control demands through passive means, by simply choosing the right surface coatings and insulation. Figure 4.4.1-9 shows MLI used for thermal control on the outside of the Upper Atmospheric Research Satellite (UARS).

We've looked at controlling heat flow into the spacecraft. Now let's consider how to control the flow out of the spacecraft. In space, surrounded by a vacuum, using conduction or convection to eject heat is possible, but not too convenient. For example, we could transfer the heat to some fluid, such as water, and then dump it overboard. The Space Shuttle uses this method to remove excess heat with a device called a *flash evaporator*. Water pumps around hot subsystems cool them by convection, and then vent overboard. Unfortunately, this method works only as long as they have extra water onboard. This is one type of active thermal control that, for long missions, is impractical.

So the most effective long-term method for ejecting heat is by radiation. To radiate heat, we must design special surface areas on the spacecraft with low absorptivity and very high emissivity (low α/ϵ). These special areas then readily emit any heat concentrated near them. These surfaces are called *radiators*. Radiators are similar to "heat windows" that allow hot components on the inside of a spacecraft to radiate their heat into the cold of space. Often a radiator is simply a section of glass coating over a particularly hot section of the spacecraft. This greatly increases the emissivity of that part of the spacecraft so more heat radiates away. The radiators on the Space Shuttle are evident on the inside of the payload bay doors, as shown in Figure 4.4.1-10.

Internal Thermal Control. Inside the spacecraft we have different problems. Often the trouble is not having too much or too little heat, but, instead, it's having the heat (or lack of it) in the right place. Each subsystem has different thermal requirements, and we must keep them all happy. Some components, such as propellant lines and tanks, need to stay warm to prevent freezing. Others, such as high-power payloads, need active cooling.

The complexity of the internal thermal control techniques depends on two things—how fast we need to move the heat and how much heat we need to move. To remove modest amounts of heat from spacecraft components when time isn't critical, the easiest way is simply to establish a heat-conduction path from the hot component to a passive external radiator. This path can be as simple as connecting the two with a piece of heat-conducting metal. This is another form of passive thermal control.

As the amount of heat and the urgency to remove it increases, we need more complex, active thermal-control methods. One of the simplest of these is to use heat pipes. *Heat pipes* are tubes closed at both ends, filled with a working fluid, such as ammonia, as shown in Figure 4.4.1-11. When one end of the pipe is close to a heat source, the fluid absorbs this heat and vaporizes. Gas pressure forces the heated vapor to the cold end of the pipe where the heat passes out of the pipe by conduction. As the vapor loses its heat, it re-condenses as a liquid. It then flows back to the other end along a wick—just as liquid flows through a candlewick.

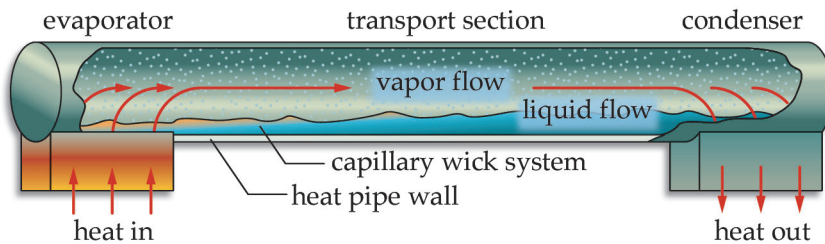


Figure 4.4.1-11. Heat Pipe. Heat pipes employ some liquid with a low boiling point inside a hollow tube. As the liquid absorbs heat at the hot end, it vaporizes and carries the heat to the cool end. There it re-condenses and “wicks” back to the hot end.

Heat pipes offer a simple, open-loop active thermal control technique. The big cooling advantage comes from the latent heat absorbed when liquids vaporize. What do we mean by this? If you heat water on the stove, how hot can it get? Only about 100°C (212°F). No matter how long it’s heated, it can reach only this temperature—the boiling point of H_2O . When you add more heat to the water, it changes phase (vaporizes) from a liquid to a gas (steam). Steam is not limited to 100°C ; it can get much hotter and thus, can store more heat. *Latent heat of vaporization* is the principle of storing additional heat in a liquid as it changes phase. If you look at the graph of energy input versus temperature for water (or almost any substance for that matter) in Figure 4.4.1-12, you’ll see where this latent heat comes in. As the fluid in a heat pipe vaporizes, it absorbs a large amount of heat due to this phenomenon.

Another simple method for removing heat is to use paraffin or some other phase-change material with a relatively low melting point to remove heat from a component during times of peak thermal demand. As the paraffin absorbs heat, it melts. When the component is no longer in use and stops producing heat, the melted paraffin conducts or radiates this heat to other parts of the spacecraft. Eventually, the thermal control system must eject the heat by radiation. As the paraffin cools, it solidifies and is ready for use during the next peak demand cycle. This thermal control method tends to be very reliable because it has no moving parts and the paraffin essentially never wears out. What makes this method so efficient is the same principle that makes ice a good thing to put in your cooler—latent heat of fusion. *Latent heat of fusion* is the same basic idea as latent heat of vaporization, but uses melting instead of boiling. As the ice melts in your cooler, it takes heat out of your sodas. We applied this principle in Section 4.1.7 to remove heat through ablation from spacecraft re-entering the atmosphere.

In many cases, heat pipes or paraffin can’t do the job, so we must resort to more complex, closed-looped, thermal-control methods. This is especially true for infra-red (IR) sensors, used on some remote-sensing missions, such as the Defense Support Program spacecraft, as shown in Figure 4.4.1-13. To be sensitive to minute changes in background temperature representing a missile launch seen from 36,000 km (22,370 mi.) away, these IR sensors must be super-cooled to 70 K (-200°C) or less. Older systems used liquid helium stored in the equivalent of large Thermos™ bottles called *Dewar flasks*. This method had a limited lifetime. After the

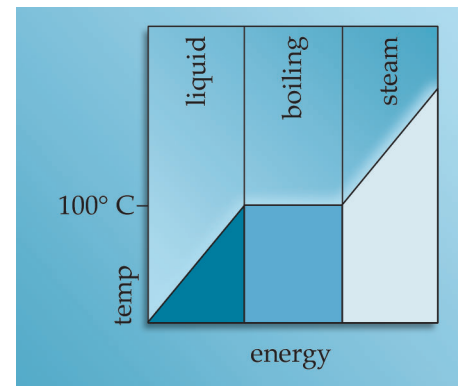


Figure 4.4.1-12. Latent Heat of Vaporization. As heat is added to a liquid, such as water, its temperature increases linearly until it reaches the boiling point. Then, the temperature of the water stays constant as more heat is added. This additional heat needed to change the phase of the substance from liquid to steam is known as latent heat of vaporization.



Figure 4.4.1-13. Defense Support Program (DSP) Spacecraft. From geosynchronous altitude the DSP spacecraft needs supercool IR sensors to detect missile launches. (Courtesy of NASA/Goddard Space Flight Center)

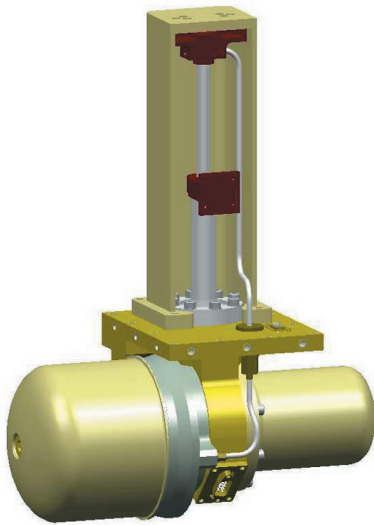


Figure 4.4.1-14. Cyro-cooler. Sophisticated cryogenic coolers, such as the one shown here, keep IR sensors at extremely low temperatures (<20 K). (Courtesy of the U.S. Air Force Research Laboratory)

liquid helium evaporated, the mission was over. Modern systems still use liquid helium, but actively cool it on the spot, using cryogenic pumps similar in concept to the pumps found in kitchen refrigerators. Advances in design and analysis of these components have drastically reduced their size, while increasing their operational lifetime to over ten years, making long-term IR remote sensing more practical and cost-effective. We show an example of an advanced cryo-cooler unit in Figure 4.4.1-14.

Section Review

Key Concepts

- Thermal control balances heat input, internal heat, and heat output to maintain thermal equilibrium
 - Sources of heat for a spacecraft include
 - The Sun
 - Earth (for spacecraft in low-Earth orbits)—from albedo and “Earth shine”
 - Internal sources—such as electrical components
 - Heat can transfer between two points in three ways
 - Conduction—heat transfer through a solid medium, the Fourier Law
 - Convection—heat transfer to a flowing fluid
 - Radiation—heat transfer by EM radiation, the Stephan-Boltzmann Law
 - All EM radiation striking a surface must be either reflected, absorbed or transmitted. Reflectivity, ρ , absorptivity, α , and transmissivity, τ , describe the percentage of each for a given surface. Once absorbed, the energy can re-radiate based on the surface emissivity, ϵ .
 - Spacecraft thermal control regulates external heat input and output, as well as internal heat flow
 - Passive thermal control uses open-loop methods, such as surface coatings, multi-layer insulation (MLI), and conduction paths, to control overall temperature.
 - Active, thermal-control techniques, such as heaters, heat pipes, and cryogenic coolers use some power and/or some working fluid to control heat in specific locations
-

4.1.1.4 Basic Principles of Life Support

In This Section You'll Learn to...

- Explain how, from the standpoint of the life support, we view humans as systems with inputs and outputs

As we described in Section 4.1.2, space is a hostile place. Charged particles, solar radiation, vacuum, and free fall are potentially harmful, even fatal, to unprepared humans. A spacecraft's life-support system provides a "home away from home" for space travelers. To understand its requirements, we can consider humans as just another system (self-loading baggage), similar to the payload or the electrical power subsystem. As such, humans have various needs that the life-support subsystem must provide. In this section, we'll focus on the basic principles that drive those needs.

In Section 4.1.2 we introduced the long-term physiological challenges of living in the space environment from charged particles, radiation, and free fall. Here we'll focus on the much shorter-term problem of staying alive (and even living comfortably) in space for days or years at a time. We already looked at the problem of thermal control. Like any other "payload," humans have their own, specific temperature range, where they function best. Now we'll look at the basic necessities to keep humans alive for even a short time in space. These include

- Oxygen—at the right pressure
- Water—for drinking, hygiene, and humidity
- Food
- Waste management

From a systems perspective, we can look at human requirements in terms of inputs and outputs. Figure 4.4.1-15 shows the amount of oxygen, water, and food an average person needs for minimum life support and the amount of waste he or she produces. Let's look at each of these requirements to better see what the life-support subsystem must deliver.

Oxygen

At sea level, we breathe air at a pressure of 101 kPa (14.7 p.s.i.). Of this, 20.9% is oxygen (O_2), 78.0% is nitrogen (N_2), 0.04% is carbon dioxide (CO_2), and the rest consists of various trace gasses, such as argon. During respiration, our lungs take in all of these gasses but only the oxygen gets used. Our bodies use it to "burn" other chemicals as part of our metabolism. Within the lungs, O_2 transfers to the blood in exchange for a metabolic by-product, CO_2 . By exhaling, we dump CO_2 back into the air around us. On Earth, plants eventually absorb this waste CO_2 and exchange it for O_2 , and the process continues. In space, it's not that simple.

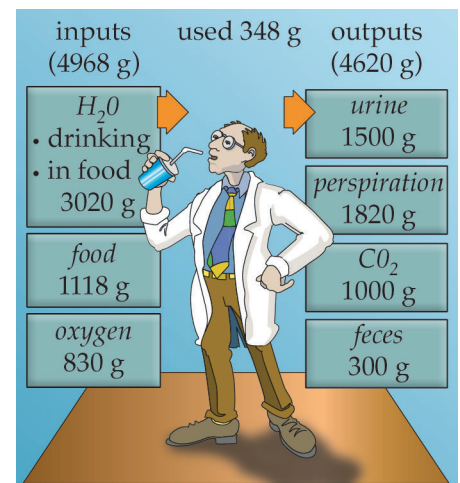


Figure 4.4.1-15. The Human System. Similar to any other system, humans take some amount of input, process it, and produce output. Here we see the approximate daily food, water, and oxygen requirements for an astronaut and the corresponding urine, perspiration, CO_2 , and feces produced. (Adapted from Nicogossian, et al and Chang, et al)



Figure 4.4.1-16. Apollo 1 Disaster. The Apollo 1 fire that claimed the life of astronauts Grissom, White, and Chaffee, was caused by the use of a pure oxygen environment inside the capsule. (Courtesy of NASA/Johnson Space Center)

To provide a breathable atmosphere in space, the life-support subsystem must provide O_2 at a high enough partial pressure to allow for comfortable breathing. *Partial pressure* refers to the amount of the total pressure accounted for by a particular gas. At sea level, the partial pressure of O_2 (PPO₂) is 20.9% of 101 kPa (14.7 p.s.i.), or about 21 kPa (3.07 p.s.i.). After becoming acclimated, people living at high altitudes (above 2000 m or about 6560 ft.) show little discomfort with PPO₂ of 13.8 kPa (2.0 p.s.i.) or less. The Space Shuttle's life-support system maintains a PPO₂ close to Earth's sea level standard at 22 ± 1.7 kPa (3.2 ± 0.25 p.s.i.).

Besides keeping the PPO₂ high enough, we must also not let it get too high. Breathing oxygen at too high of a partial pressure is literally toxic. This is a problem which scuba divers must also avoid during deep dives. We consider a PPO₂ of less than 48 kPa (7 p.s.i.) safe.

Besides providing adequate oxygen to breathe, we must consider other trade-offs. We want the PPO₂ to be low enough so it doesn't create a fire hazard in the crew cabin. This was the problem during the Apollo 1 accident, shown in Figure 4.4.1-16. At that time, the cabin atmosphere was pure oxygen. This led to the untimely deaths of three astronauts, when a wiring problem caused a fire during a routine ground test. The pure oxygen atmosphere let the fire spread much more rapidly than it would have in a normal O_2/N_2 atmosphere. Since then, cabin atmospheres in U.S. manned spacecraft have contained a mixture of oxygen and nitrogen to decrease this fire hazard.

The correct mixture and pressure of gasses is also important for thermal control. Convective heat transferred into the cabin atmosphere also cools electronic components, so atmospheric composition and circulation must support that function.

A final concern for cabin air is the astronauts preparing to leave the spacecraft for an extravehicular activity (EVA or space walk). Because of design limitations, Shuttle space suits operate at 29.6 kPa (4.3 p.s.i.). To avoid potential decompression problems, the astronauts reduce the Shuttle pressure to 70.3 kPa (10.2 p.s.i.) 12 hours before a planned EVA. Even then, they must breathe pure oxygen for 3–4 hours before the EVA, to purge nitrogen from their bodies. Otherwise, the nitrogen could form bubbles in the blood, causing a potentially deadly problem known as "the bends," a condition that scuba divers must also carefully avoid. However, given the relative infrequency of EVAs, most astronauts consider these procedures a minor inconvenience.

Where does the air for the life-support subsystem come from? For Space Shuttle missions, tanks hold liquid oxygen and liquid nitrogen. As liquids, they need much less volume than as gasses. The life support system warms the liquids and then evaporates them into gases at the correct partial pressures. This process also replenishes air that vents during space walks or leaks out.

It's important to recognize that astronauts need an efficient, closed-loop control system to monitor and maintain a safe atmosphere. Sensors continually monitor the pressure and composition of cabin air and alert the crew and ground controllers to any problems before they can become a health hazard.

Water and Food

With an understanding of the air-supply system, we can now turn our attention to one of the simpler pleasures of life—eating and drinking. We normally eat and drink without much concern for the total mass that we consume (we're much more concerned with calories!). For space missions, every gram taken to orbit represents a huge cost, so we want very little waste. On the other hand, because a crew can't call out for pizza, they must carry enough water and food for any contingency. Thus, we must fully understand the crew's needs when we design this piece of the ECLSS.

Astronauts need water onboard for many reasons. As a minimum, humans need about two liters of drinking water per day (about 2 kg or 4.4 lb.) to stay alive. We also need another liter or so of water for food preparation and re-hydration. Besides this minimal amount of water to maintain life, astronauts need water for personal hygiene (washing, shaving, etc.), as well as, doing the dishes and washing clothes. All told, this can add up to more than 20 liters per person per day.

We also need food. The average human needs about 29 calories per kilogram of body weight per day, to maintain their present weight. This means a typical 70 kg (154 lb.) astronaut needs at least 1972 calories per day—more for days when strenuous EVAs occur.

Space food has come a long way since astronauts ate peanut butter and drank Tang from tubes during the Gemini missions. Nowadays, astronaut food isn't much different from what we're used to on Earth. Figure 4.4.1-17 shows an astronaut "sitting down" to a healthy meal with a tray strapped to her thigh. Planners use the recommended daily allowances (RDA) of carbohydrates, protein, fat, vitamins, and minerals that we read about on food labels. To conserve mass and volume, they dehydrate or freeze-dry much of the food and then rehydrate it on orbit. For short-term missions, astronauts take fresh fruit and other perishable items—storage space and mass permitting. Depending on how they package it and the total calories needed, they must plan as much as 2 kg of food per person per day.

Where does all this food and water come from? For U.S. manned flights during Apollo and on the Space Shuttle, ample water comes as a by-product of the fuel cells used to produce electrical power. Thus, astronauts have had the luxury of using as much water as they want. They simply dump wastewater overboard into the vacuum of space. Menu planners help them order all the necessary food for their mission. For extended missions lasting several months or more, such as those flown on the Russian Mir space station, unmanned re-supply spacecraft are launched every few months with more groceries.

Waste Management

Humans produce waste in the form of urine, feces, and CO_2 , simply as a by-product of living. Collecting and disposing of this waste in an effective and healthy manner is one of the biggest demands on the life-support



Figure 4.4.1-17. Food in Space. Food astronauts eat isn't all that different from Earth food. However, to save space, more dehydrated and freeze-dried foods are often used. Above you can see a typical meal tray used on the Shuttle. (Courtesy of NASA/Johnson Space Center)

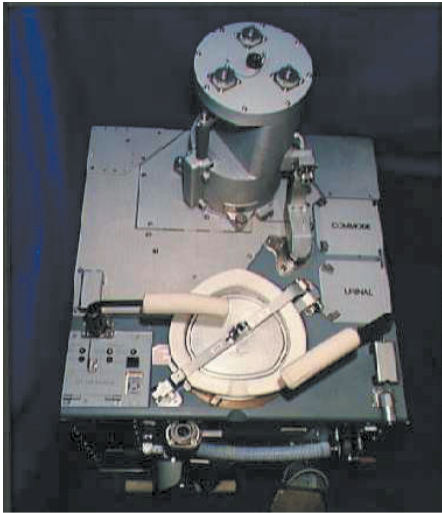


Figure 4.4.1-18. Shuttle Toilet. The toilet used by astronauts on the Space Shuttle compensates for the free-fall environment. On Earth, gravity does all the work; in free fall, forced air creates a suction to draw waste away from the body. (Courtesy of NASA/Johnson Space Center)



Figure 4.4.1-19. "Scrubbing CO₂." Lithium hydroxide canisters, like the ones being changed here, remove carbon dioxide (CO₂) from the air on the Space Shuttle. (Courtesy of NASA/Johnson Space Center)

subsystem. Urine and feces pose health risks, as well as odor problems. CO₂ poses a subtler problem. Unless they remove it from the air, its concentration builds up, eventually causing increased heart and respiratory rates, a change in the body acidity, and other health complications.

One of the most commonly asked questions of the entire space program is, "How do you go to the bathroom in space?" Collecting urine and feces in a free-fall environment is a challenge. In the early days of the space program, designers subjected those dashing young astronauts with the "right stuff" to a most humbling experience. They collected urine and feces using inconvenient and messy methods, euphemistically called *intimate-contact devices*. Because all the U.S. astronauts were male at that time, they collected urine using a roll-on cuff placed over the penis and connected to a bag. They collected feces using a simple diaper, or, even more messy, a colostomy-type bag taped or placed over the buttocks. They either dumped urine and feces overboard (to eventually burn up in the atmosphere) or returned them to Earth for analysis and disposal.

The Skylab program ushered in a new era in free-fall toilets. For the first time, intimate contact devices were no longer necessary. An advanced version of this system is now on the Space Shuttle, as shown in Figure 4.4.1-18. However, the free-fall toilet created (and still creates) considerable challenge to engineers. We tend to take for granted all the work that gravity does for us every time we go to the bathroom.

On Earth, urine and feces fall away from our bodies; in orbit, it's a different story. In free fall, we, our urine, and our feces are all falling at the same rate. As a result, waste isn't compelled to move away from us, so it tends to float next to our body in a smelly blob (or, as one anonymous astronaut put it "those little guys just don't want to leave home!"). To get around this problem, engineers use forced air to create a suction, pulling urine and feces into a waste-collection system for disposal. Unfortunately, this method doesn't work nearly as well as good ol' gravity, but at least it's a vast improvement over the older methods.

In comparison, removing CO₂ from the air is much simpler and far less messy. On the Space Shuttle, canisters containing charcoal and lithium hydroxide (LOH) filter the air. The LOH chemically reacts with the CO₂, trapping it in the filter. The charcoal absorbs odors and other contaminants, as well. The crew must change these canisters periodically during the flight as we show one astronaut doing in Figure 4.4.1-19. On Skylab, for missions lasting up to 84 days, the crew filtered CO₂ using a molecular sieve, which they then "baked out" and re-used.

Closed-loop Life Support

From a systems point of view, astronaut and cosmonaut life support systems have been largely open loop in nature. Certainly, there are closed-loop aspects that monitor temperature and cabin atmosphere, but all of the system inputs (air, water, food) are eventually thrown away as waste.

For future long-term missions to the Moon or Mars, lasting many months or years, it probably won't be practical to take along all the

supplies or rely on re-supply missions. Instead, we need to establish a closed system that can reclaim and recycle water and other waste. Such closed-loop systems could recycle urine, feces, and CO_2 to provide water and food to the crew, as illustrated in Figure 4.4.1-20. While this may not sound appetizing, it promises to greatly reduce the mass they need to pack along for very long missions. Scientists are investigating life-support subsystems that can effectively reclaim and recycle water, the heaviest item. One limited approach to this idea is to reclaim so called “gray” water (used for washing and rinsing) and reuse it for purposes other than drinking.

Other scientists are looking beyond such limited systems to ones that will fully recycle nearly everything onboard and provide all the oxygen, water, and food crew members need for missions lasting for years. Such systems could eventually make it much easier for astronauts to eat, drink, breath, and even go to the bathroom. Unfortunately, such systems are still far in the future. Until then, these pioneers in the high frontier must accept some austere conditions.

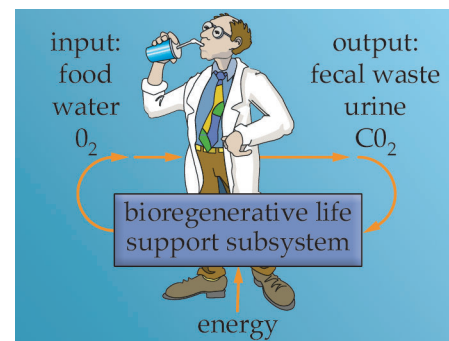


Figure 4.4.1-20. Bioregenerative Life-support Subsystems. For long space missions to Mars or beyond, bioregenerative life support sub-systems may be needed. These systems allow us to “close the loop” and recycle all human waste into food, water, and oxygen.

Section Review

Key Concepts

- Life support keeps humans alive in space. Humans need
 - Oxygen at the right partial pressure
 - Water and food
 - Methods for waste disposal (CO_2 , urine, and feces)

4.1.1.5 Systems Engineering

In This Section You'll Learn to...

- Apply space-systems engineering to the design and testing of the ECLSS
-

Now that you've warmed up to the concepts of thermal control and life support, we can return our attention to the systems engineering challenges of ECLSS design. We'll look briefly at the inputs to the design process, then review some of the testing requirements spacecraft must endure before launching into the harshness of space.

Requirements and Constraints

Remember we kicked off the space systems-engineering process by defining mission and system-level requirements and constraints. Of course, the biggest driver for the ECLSS design is whether the mission includes a fragile human payload. With astronauts onboard, we must include all of the necessary life support systems that we discussed earlier—water, air, food, and waste management. To total these requirements, we multiply the daily human requirements by the number of astronauts and the total mission duration. This gives us a starting point for designing the ECLSS *life-support budget*.

Without humans to worry about, the “LS” part of ECLSS goes away and environmental control remains. This system must mainly keep components at the right temperature. Unlike mission data or electrical power, the thermal budget is a collection of acceptable operating temperature ranges for each subsystem. System engineers must look at component placement, conduction paths, and thermal input and output to ensure each subsystem stays comfortable.

Analysis and Design

At the beginning of the section, we introduced the concept of thermal equilibrium. Recall that to maintain this state, the heat output must balance the heat input plus internal heat. The biggest challenge of the thermal control system design is meeting this requirement under all mission conditions. Keeping things warm isn't a problem in full sunlight. Keeping things cool isn't a big problem in the darkness of space. But keeping them cool in the sun and warm in the shade can be a big problem.

During the design loop, thermal control engineers must stay closely involved with the other subsystem designers to understand their requirements and carefully analyze where all the heat will go. One method for managing heat flow is to create a detailed thermal model of the entire system, by dividing it into a series of nodes. A *thermal node* is any payload,

subsystem or even part of the structure that has unique thermal properties to consider. We carefully define the thermal properties of each node (heat input, absorptivity, emissivity, etc.). We then connect all of the nodes, in a virtual sense, as illustrated in Figure 4.4.1-21, and calculate the equilibrium temperature using a complex computer simulation. We show the output of one such simulation in Figure 4.4.1-22. The results give designers a good indication of potential thermal problems, and help them design passive and active thermal control techniques to take care of them.

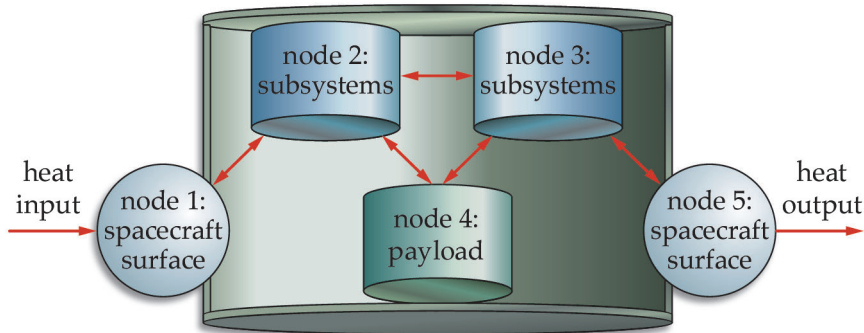


Figure 4.4.1-21. Spacecraft Thermal Analysis Techniques. To model spacecraft thermal control, engineers define a series of interconnected nodes on the spacecraft. By defining the unique thermal properties of each node and understanding the heat conduction and radiation between nodes, they can use computer analysis techniques to determine overall system temperatures.

Testing

Finally, when we finish a design, we must validate it against the original requirements. For thermal control, this involves a testing process that subjects the spacecraft to the simulated vacuum and temperature conditions of space. To test temperature extremes, we perform thermal cycling tests (hot-cold-hot-cold, etc.) on individual components, subsystems, and the entire spacecraft, as shown in Figure 4.4.1-23. These tests subject components to the wide temperature extremes they'll see on orbit. These tests also determine if thermal cycling may cause them to fail.

In addition to relatively inexpensive thermal-cycling tests, we add a strong vacuum to the thermal cycling, using large, more expensive thermal/vacuum facilities, as shown in Figure 4.4.1-24. These "thermal-vac" tests create realistic heat transfer situations by eliminating convective cooling processes (no air). If the spacecraft survives these grueling series of tests, we certify the ECLSS ready to fly!

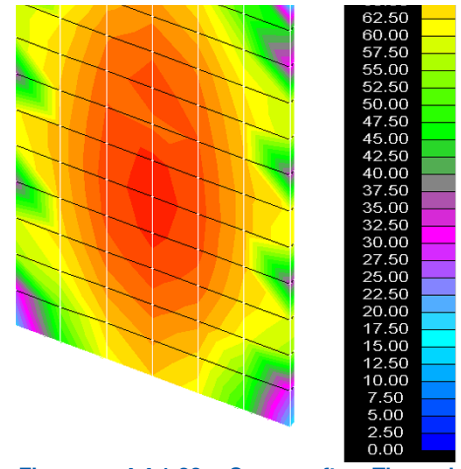


Figure 4.4.1-22. Spacecraft Thermal Analysis Results. This solar panel shows the distribution of temperatures ($^{\circ}\text{C}$) as a result of a computer thermal simulation. (Courtesy of Surrey Satellite Technologies, Ltd., U.K.)



Figure 4.4.1-23. Thermal Cycling. These tests screen components to ensure they'll function in the space environment by subjecting them to a series of thermal cycles—hot-cold-hot-cold. Here we show the Picosat microsatellite in a small thermal cycling chamber. (Courtesy of Surrey Satellite Technology, Ltd., U.K.)



Figure 4.4.1-24. Thermal Vac Facility. Prior to flight, individual subsystems, and entire spacecraft, go through thermal cycling tests inside large vacuum chambers to simulate the effects of the space environment. (Courtesy of Hughes Space and Communications, Co.)

Section Review

Key Concepts

- Systems engineering for the ECLSS is driven by life-support budgets and individual operating temperature ranges for each payload and subsystem
 - Engineers do thermal analysis by simulating each component as a series of nodes with specific thermal properties
 - Spacecraft testing involves subjecting components and entire systems to thermal cycling, as well as combined, thermal-vacuum facilities
-

References

- Asimov, Isaac. *Asimov's Biographical Encyclopedia of Science and Technology*. Garden City, NJ: Doubleday and Company, Inc., 1972.
- Beer, Ferdinand P. and Russel E. Johnson, Jr. *Statics and Mechanics of Materials*. New York, NY: McGraw-Hill Inc., 1992.
- Chang, Prof. I. Dee (Stanford University), Dr. John Billingham (NASA Ames), Dr. Alan Hargen (NASA Ames). "Colloquium on Life in Space." Spring, 1990.
- Chetty, P.R.K. *Satellite Power Systems: Energy Conversion, Energy Storage, and Electronic Power Processing*. George Washington University Short Course 1507. October 1991.
- Chetty, P.R.K. *Satellite Technology and Its Applications*. New York, NY: THB Professional and Reference Books, McGraw-Hill, Inc., 1991.
- Doherty, Paul. "Catch a Wave." *Exploring*. Vol. 16, No. 4, (Winter, 1992): 18–22.
- Gere, James M. and Stephen P. Timoshenko. *Mechanics of Materials*. Boston, MA: PWS Publishers, 1984.
- Gonick, Larry and Art Huffman. *The Cartoon Guide to Physics*. New York, NY: Harper Perennial, 1991.
- Gordon, J.E. *Structures: Why Things Don't Fall Down*, New York, NY: Da Capp Press, Inc., 1978.
- Gunston, Bill. *Jane's Aerospace Dictionary*. New Edition. London, U.K.: Jane's Publishing Co., Ltd., 1986.
- Holman, J.P. *Thermodynamics*. New York, NY: McGraw-Hill Book Company, 1980.
- MacElroy, Robert D. Course Notes from AA 129, Life in Space, Stanford University, 1990.
- Nicogossian, Arnauld E., Huntoon, Carolyn Leach, Sam L. Pool. *Space Physiology and Medicine*. 2nd Edition, Philadelphia, PA: Lea & Febiger, 1989.
- Pitts, Donald R. and Leighton E. Sissom. *Heat Transfer*. Schaum's Outline Series. New York, NY: McGraw-Hill, Inc., 1977.
- Poole, Lon. "Inside the Processor," *MacWorld*. October 1992, pp. 136–143.
- Sarafin, Thomas P. *Spacecraft Structures and Mechanisms*. Dordrecht, the Netherlands: Kluwer Academy Publishers, 1995.
- Wertz, James R. and Wiley J. Larson. *Space Mission Analysis and Design*. Third edition. Dordrecht, Netherlands: Kluwer Academic Publishers, 1999.

